Turbulent Small-scale Dynamo (SSD) Action in Solar Surface Simulations

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Outline

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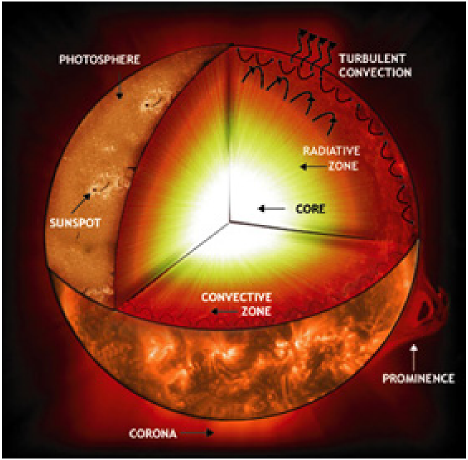
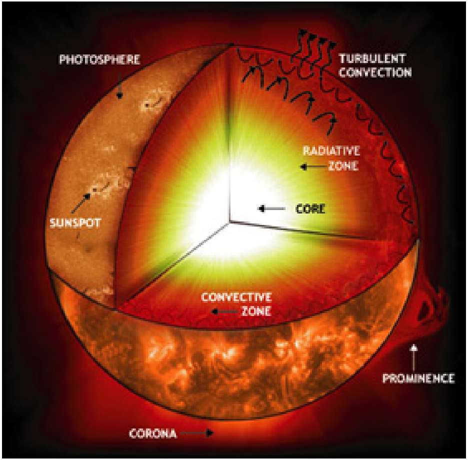
1. Motivation: intra-network quiet-Sun B
   - Observed small-scale B
   - A lot of magnetic flux and energy
   - What is its source?
2. Small-scale dynamo (SSD) in realistic photospheric simulations?
   - Which realistic dynamo simulations?
   - What is a turbulent SSD and ...
   - ...how do we tell?

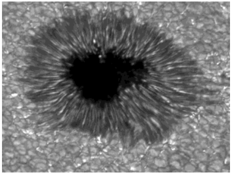
Solar overview



http://www.ece.unm.edu/ plasma/Space/solar.html

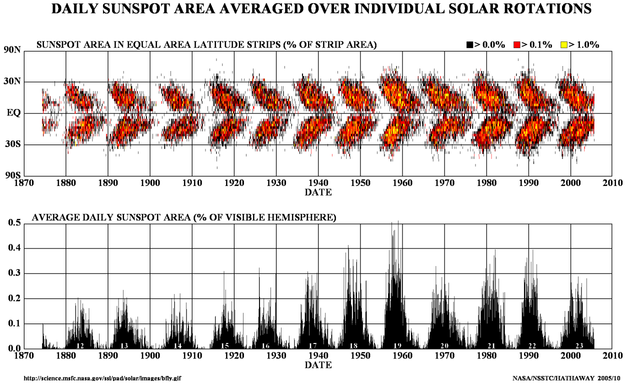
Solar overview





http://www.ece.unm.edu/ plasma/Space/solar.html

Sunspot cycle

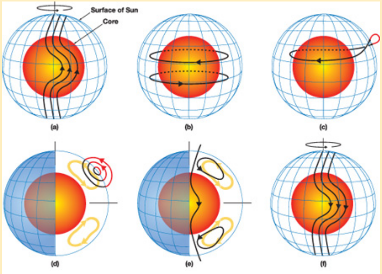


Sunspot, http://en.wikipedia.org/w/index.php?title=Sunspot&oldid=342856201

Solar global dynamo

Global dynamo

- 22 year cycle
- ≈ dipolar
- many models (Babcock-Leighton, flux-transport (Dikpati et al.), surface shear (Brandenburg 2005))

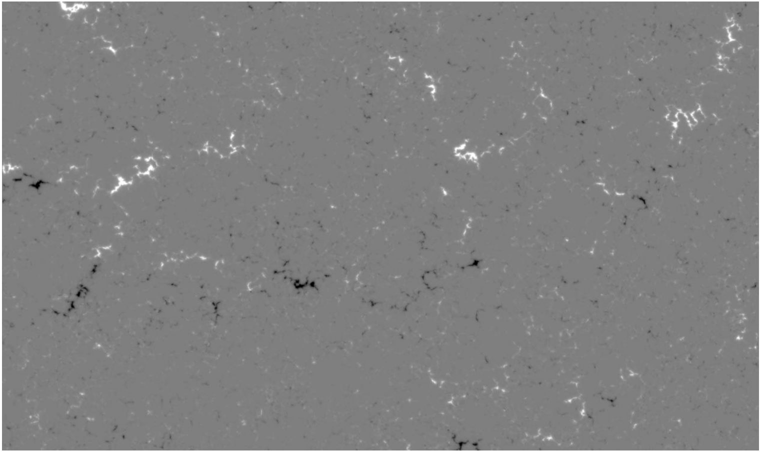


M. Dikpati, NCAR

Network quiet-Sun magnetic field

Lites et al. 2008

$3\sigma < |B_z| < 500\,\mathrm{G}$



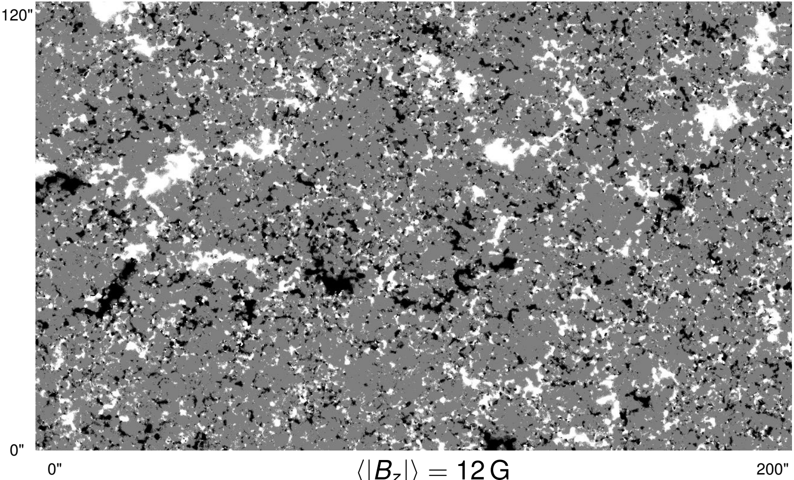
$\sigma = 2.4\,\mathrm{G}$

$\langle |B_z| \rangle = 12\,\mathrm{G}$

Intra-network quiet-Sun magnetic field

Lites et al. 2008

$3\sigma < |B_z| < 24\,\mathrm{G}$



$\sigma = 2.4\,\mathrm{G}$

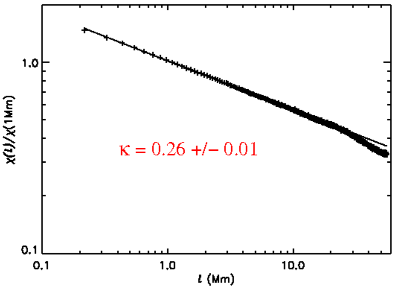
$\langle |B_z| \rangle = 12\,\mathrm{G}$

Magnetic carpet (Title and Schrijver 1998; Title 2000;Hagenaar et al. 2003)

Cancellation is self-similar

Pietarila Graham et al., *ApJ* **693**, 1728-1735, 2009

Hinode observation

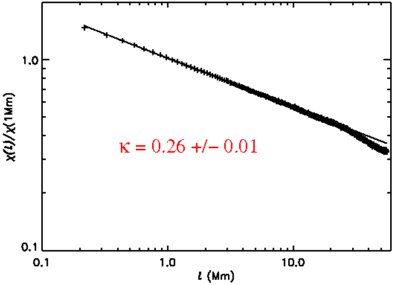


Portion of flux remaining after degrading resolution $\propto$ resolution$^{-\kappa}$

Cancellation is self-similar

Pietarila Graham et al., *ApJ* **693**, 1728-1735, 2009

Hinode observation



Portion of flux remaining after degrading resolution $\propto$ resolution$^{-\kappa}$

What it tells us

- Size of magnetic structures $\leq$ 20 **km**
- Resolution-independent, true $\langle|B_Z|\rangle \geq$ 40 **G**

A lot of small-scale flux

- $\langle|B_Z|\rangle > 40\,\mathrm{G}$
  $\langle|B|\rangle \sim 100\,\mathrm{G}$ Hanle (Trujillo Bueno et al. 2004) **@ 90% surface area**
- More unsigned magnetic flux and energy than active regions even during solar maximum (Sánchez Almeida 2004, Trujillo Bueno et al. 2004)
- 10 times energy to heat chromosphere and corona (Trujillo Bueno et al. 2004)

Where does all this small-scale flux come from?

Turbulent small-scale dynamo (SSD)?

- More than active regions
- *Not* dependent on solar cycle or on latitude (Hagenaar et al. 2003, Sánchez Almeida 2003, Trujillo Bueno et al. 2004)
- Petrovay & Szakaly (1993): not decay of active regions nor flux tubes → need source term: SSD?

Where does all this small-scale flux come from?

Other possibilities

- "Turbulent cascade" to small scales of large-scale **B**
- Turbulent fluid motions stretching large-scale $\mathbf{B}_0$: Alfvénic turbulent induction (Schekochihin et al. 2007)

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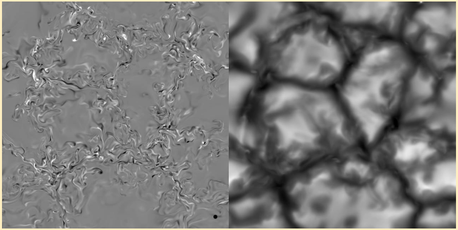
The MURaM code (Vögler et al. 2005; Vögler 2003)

Realistic magnetoconvection

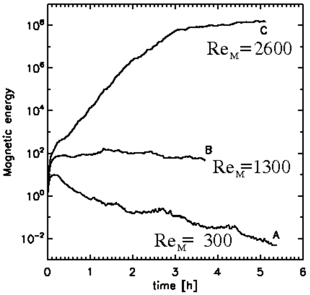
- Strong stratification
- Fully compressible
- Partial ionization
- Radiative transfer
- Open lower boundary

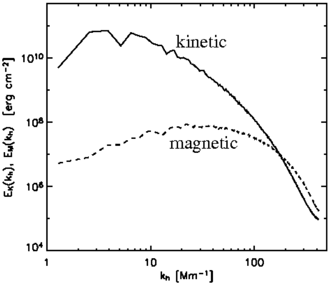
  (vertical upflows, $\frac{dv}{dz} = 0$ for downflows; B_{hor} not advected into box)
- No rotation
- Parallelized

B_z & brightness



The MURaM dynamo (Vögler & Schüssler 2007)

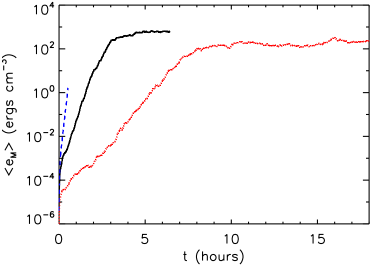




Run	$N_{hor}^2 \times N_Z$	Re_M
C	$648^2 \times 140$	2600

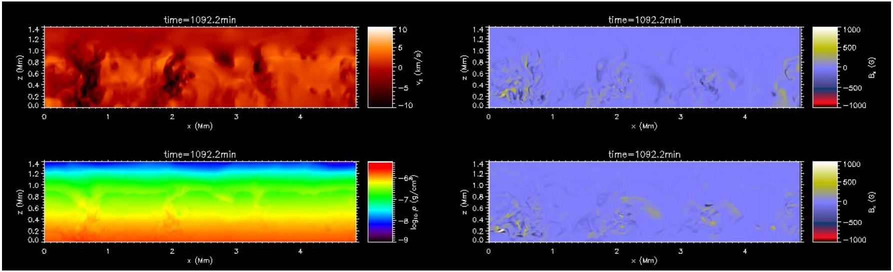
Our simulations

Run	Grid (km)	$P_{M,\mathrm{eff}}$	η $\mathrm{cm}^2\ \mathrm{s}^{-1}$	Re_M
1	$9^2 \times 10$	~ 2.0	$1.6 \cdot 10^{10}$	≈ 2100
2=C	$7.5^2 \times 10$	~ 1.3	$1.25 \cdot 10^{10}$	≈ 2600
3	$5^2 \times 7$	~ 1.1	$6.25 \cdot 10^{9}$	≈ 5300
4	$4^2 \times 4$	-	$4 \cdot 10^{9}$	≈ 8300

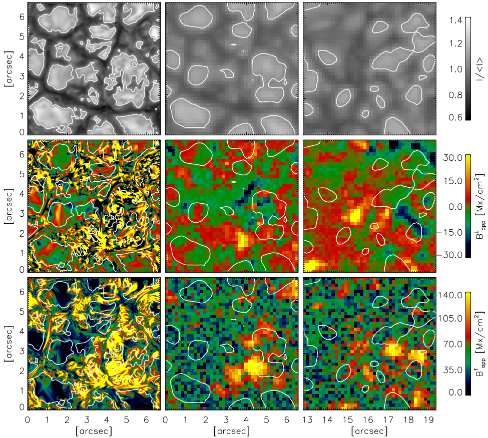


Structure of MURaM dynamo

Run 1

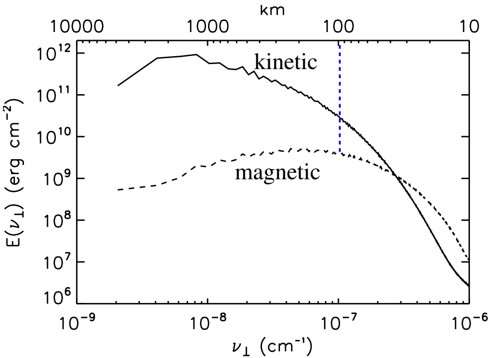


Appearance of MURaM dynamo (Danilovic et al. 2010)



Run 2

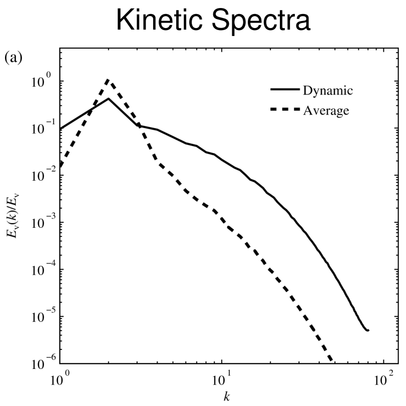
Is it a SSD?

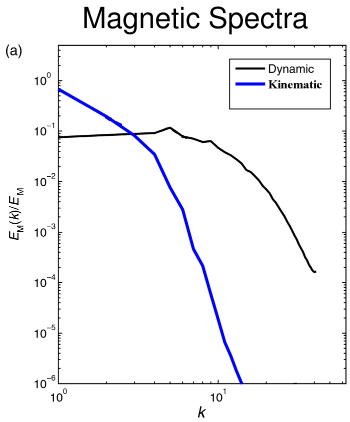


Run 3

Small-scale field $\nRightarrow$ SSD (Ponty et al. 2007)

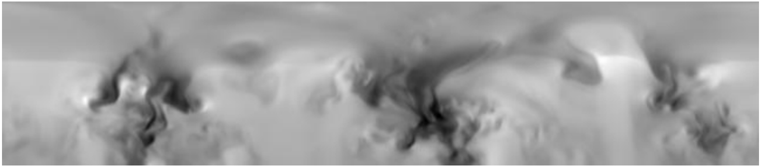
Alternate source: time-averaged mean flow





MURaM mean flow

Instantaneous flow



Time-averaged mean flow

Our goal: distinguish between possible sources

Alexakis et al. 2007

3 Possible sources

- Turbulent energy cascade
- Stretching of large-scale $\mathbf{B}_0$ – Alfvénic response to small-scale velocity fluctuations
- Stretching of small-scale field – SSD

What is a turbulent dynamo?

Turbulent dynamo

- Stretching of B-field lines by turbulence (Batchelor 1950, Moffat 1978, Parker 1979)
- "Fast" dynamo for chaotic & sufficiently complex flows (Childress & Gilbert 1995)

Stretching $\gg \eta$

$$\partial_t \mathbf{B} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$Re_M = \frac{v_o l_o}{\eta} > Re_M^C \rightarrow \text{dynamo}$$

What *does* SSD look like?

$$P_M \equiv \frac{\nu}{\eta} \geq 1$$

Schekochihin et al. 2004

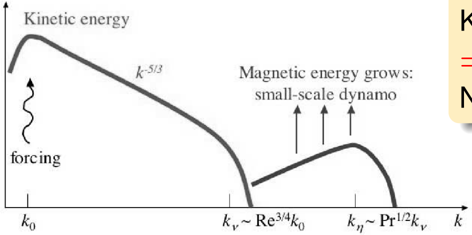


FIG. 1.—Sketch of scale ranges and energy spectra in a large-Pr_m medium.

eddies $l_\nu > l_\eta$ stretch B

Growth rate, γ

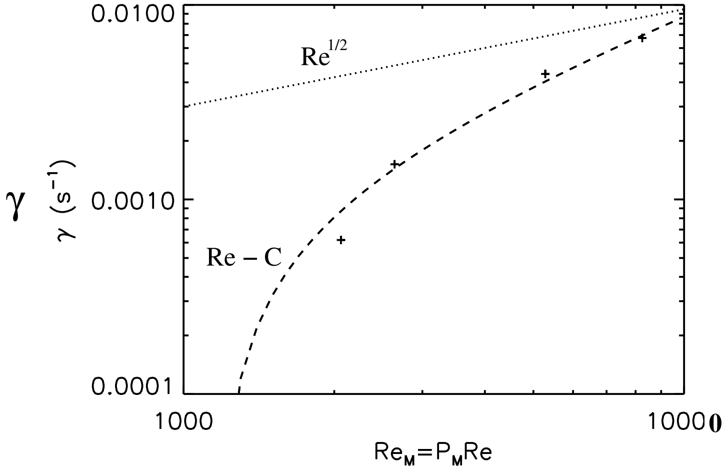
$\gamma^{-1} \sim \tau_l \sim \frac{l}{v}$

K41: $v \sim l^{1/3}$, $l_\nu \sim Re^{-3/4}$

$\Rightarrow \gamma \sim Re^{1/2}$

Never yet seen (Schekochihin et al. 2004)

MURaM growth rate

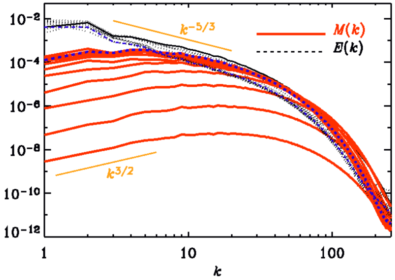


Kazantsev 1968 model of SSD

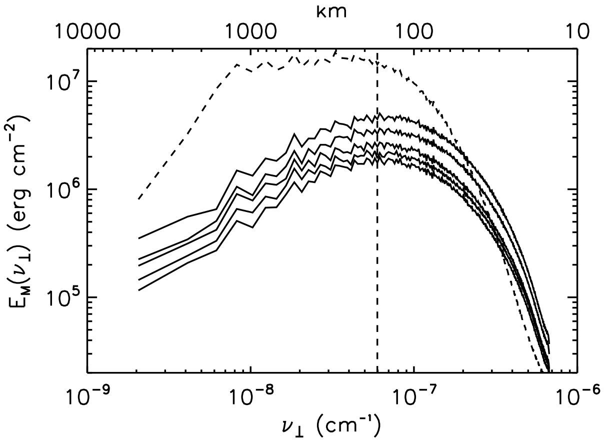
Kazantsev 1968 model

- Analytical, *isotropic*, kinematic model
- $M(k) \equiv E_M(k) \propto K_0(k) e^{\lambda \bar{\gamma} t} k^{+3/2}$
- All modes grow at same rate
- $k^{+3/2}$

Brandenburg 2004



MURaM looks similar



Re_M	exponent
2100	0.5
2600	0.6
5300	0.8

How do we know at what scales?

Incompressible transfer functions (Alexakis et al. 2005, Mininni et al. 2005)

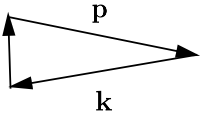
What does a transfer function do?

- $E_M = \frac{1}{8\pi}|\mathbf{B}|^2$
  $\partial_t 4\pi E_M = \mathbf{B}\cdot[\partial_t \mathbf{B}] = \mathbf{B}\cdot\left[\nabla\times(\mathbf{v}\times\mathbf{B}) + \eta\nabla^2\mathbf{B}\right]$

$$
\begin{aligned}
E_M(\mathbf{k}) &= \frac{1}{8\pi}\hat{\mathbf{B}}^*(\mathbf{k})\cdot\hat{\mathbf{B}}(\mathbf{k}) \\
\partial_t 4\pi E_M(\mathbf{k}) &= \underbrace{\hat{\mathbf{B}}^*(\mathbf{k})\cdot\mathfrak{F}[-\mathbf{v}\cdot\nabla\mathbf{B}}_{T_{BB}(k)} + \underbrace{\mathbf{B}\cdot\nabla\mathbf{v}}_{+T_{VB}(k)} + \underbrace{\eta\nabla^2\mathbf{B}]}_{+D(k)}(\mathbf{k}) \\
\partial_t E_M(\mathbf{k}) &= T_{BB}(k) + T_{VB}(k) + D(k)
\end{aligned}
$$

- Convolution theorem: $\mathfrak{F}\left[v\cdot B\right](k) = \int_{-\infty}^{\infty}\hat{v}(k-p)\cdot\hat{B}(p)dp$

$\mathbf{q}\equiv\mathbf{k}-\mathbf{p}$



Work against/by magnetic tension force

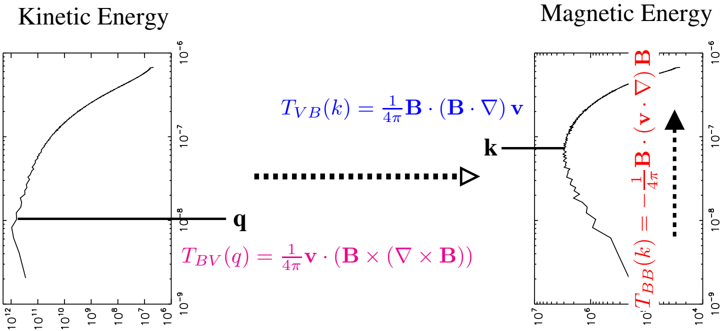
$$\hat{\mathbf{v}}^* \cdot \mathfrak{F}[\partial_t \hat{\mathbf{v}} \quad \overbrace{+\mathbf{v}\cdot\nabla\mathbf{v} + \nabla(P + \frac{1}{2}|B|^2)}^{T_{VV}(k)} = \overbrace{\mathbf{B}\cdot\nabla\mathbf{B}}^{T_{BV}(k)} \quad + \overbrace{\nu\nabla^2\mathbf{v}}^{D_\nu(k)}]$$

$$\Updownarrow$$

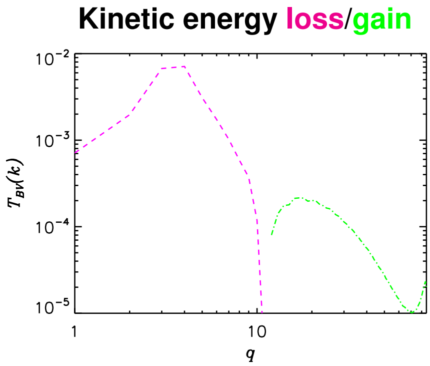
$$\hat{\mathbf{B}}^* \cdot \mathfrak{F}[\partial_t \hat{\mathbf{B}} \quad \underbrace{+\mathbf{v}\cdot\nabla\mathbf{B}}_{T_{BB}(k)} = \underbrace{\mathbf{B}\cdot\nabla\mathbf{v}}_{T_{VB}(k)} \quad + \underbrace{\eta\nabla^2\mathbf{B}}_{D_\eta(k)}]$$

How do we know from where?

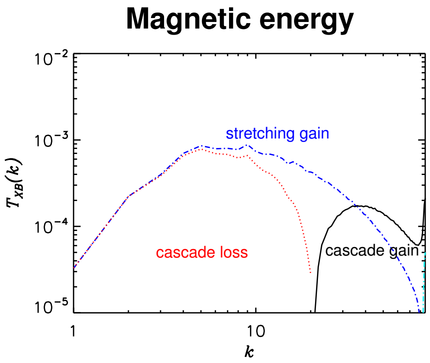
Incompressible transfer functions (Alexakis et al. 2005, Mininni et al. 2005)



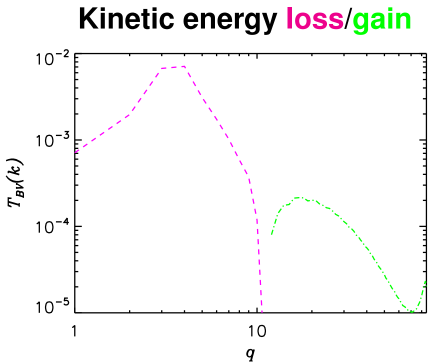
Isotropic, incompressible dynamo example

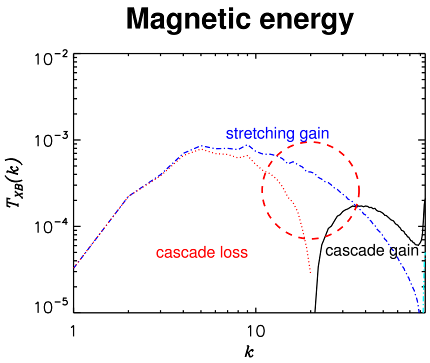


Isotropic, incompressible dynamo example

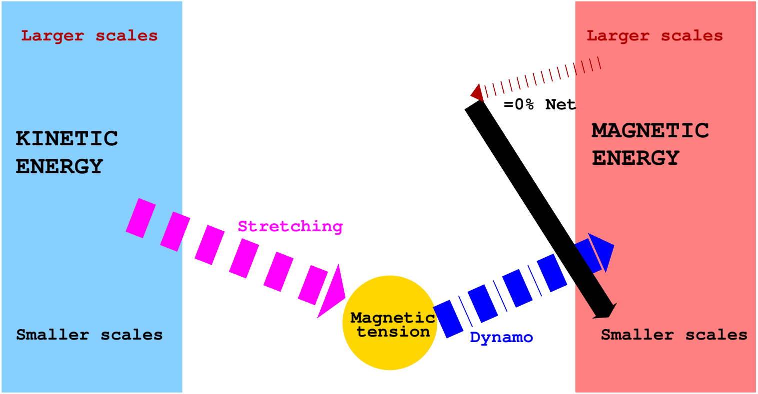


Isotropic, incompressible dynamo example



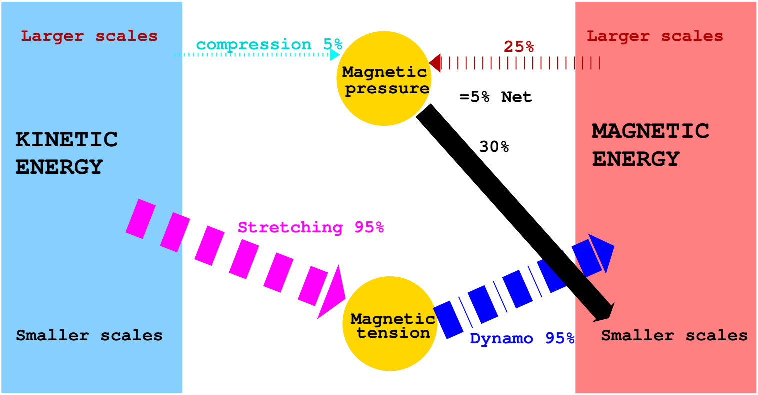


Summary of incompressible MHD transfer



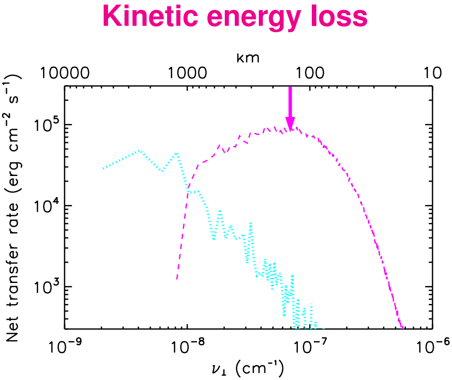
Extend transfers functions to compressible MHD

Pietarila Graham et al. 2010, arXiv:1002.2750



MURaM dynamo transfer analysis

Pietarila Graham et al. 2010, arXiv:



MURaM dynamo transfer analysis

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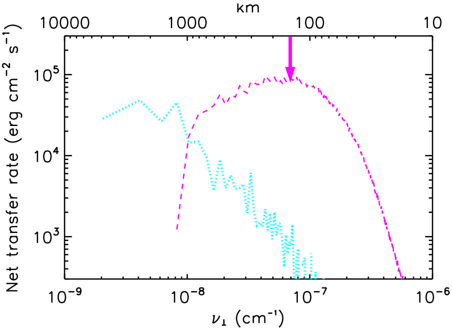
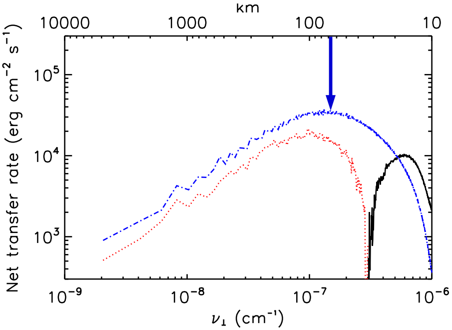
Kinetic energy loss



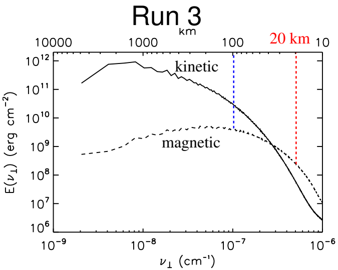
Magnetic energy gain

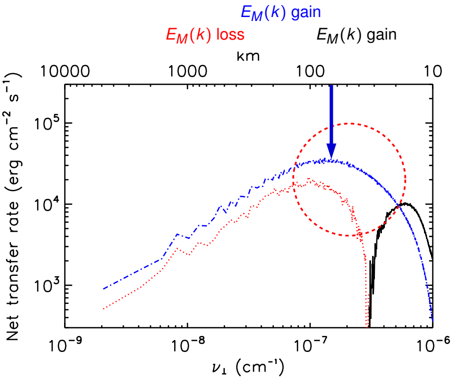


Rule out: cascade

Analysis

1. Cascade below $\sim$ 20 km
2. **B** generated at $\sim$ 65 km





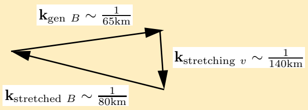
Rule out: Alfvénic turbulent induction

Analysis

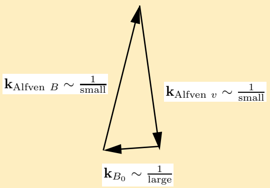
1. **B** generated at $\sim$ 65 km
2. Dynamo driven by $\sim$ 140 km motions
3. Triad $\Rightarrow$ *stretched B* at $\sim$ 80 km

Re_M	ν_{gen}^{-1}	ν_v^{-1}	$\nu_{stretch}^{-1}$
2100	110 km	200 km	160 km
2600	100 km	180 km	140 km
5300	65 km	140 km	80 km

Small-scale dynamo



Alfvénic



Summary

MURaM small-scale dynamo

- Small-scale field produced by SSD
  - Not “compressive cascade”
  - Not Alfvénic turbulent induction
- SSD should play a role in the Sun as well